STABILITY OF SHIPS WITH LARGE BREADTH-DRAFT RATIO IN FOLLOWING AND QUARTERING SEAS

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SUMMARY

The International Maritime Organization (IMO) decided to revise its intact stability criteria from prescriptive based criteria to be the performance based one. The new criteria should be capable to investigate stability failure in seaways such as dead ship condition, pure loss of stability, parametric rolling and broaching. In case of pure loss of stability in following and quartering seas, delegation of Japan and USA proposed vulnerability criteria level one based on the hull form characteristics of ships. These proposed criteria have been tested by using several different hull forms. However similar characteristics with the Indonesian ro-ro ferries have never been used to validate the criteria. The main characteristics of Indonesian ro-ro ferries are small draught with large breadth or large ratio of breadth and draught. Therefore it is important to investigate the pure loss of stability in following and quartering seas in order to investigate effect of some variables.

This paper discusses about effects of wave direction, significant wave height and ship speed on roll motion characteristics of ships with large ratio of breadth and draught in irregular following and quartering seas. Two degree of freedom model is used to investigate the roll motion characteristics. The irregular wave is developed by using the ITTC wave spectrum and the linear and nonlinear damping coefficients of roll are estimated by using the Ikeda semi empirical method. The results show that the significant wave height has significant effect on the roll motion in following and quartering seas. Eventhought the ship may safely operate in the significant wave height of 2.25 meters with maximum roll angle of 0.545 radian or 31 degrees. In higher significant wave height, capsizing dangerous may occur due to pure loss of stability. The maximum roll angle does not significantly change due to alteration of the heading angle from wave direction. It means that the heading angle does not significant effect on roll motion in following and quartering seas. When the intial forward speed increases, the maximum roll angle decreases. However in a certain initial forward speed, the maximum roll angle increases because occurrence of resonance. This phenomena show that dangerous condition due to pure loss of stability may be avoided by change the ship speed.

NOMENCLATURE

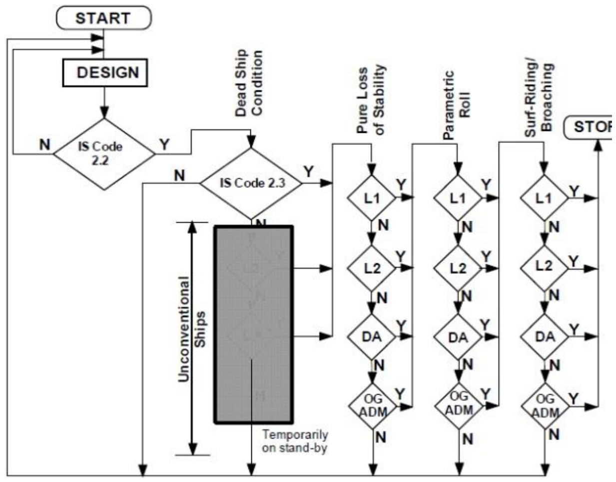
A_{11}	Added mass in surge motion
A_{44}	Added inertia of roll motion
B_L	Linear damping coefficient of roll (s^{-1})
B_N	Nonlinear damping coefficient of roll (rad^{-1})
$B(x)$	Breadth of ship section (m)
D	Propeller diameter (m)
GZ_S	Righting arm in calm water (m)
GZ_W	Righting arm in wave (m)
J	Advance coefficient
$K_T(J)$	Trust coefficient
M_W	Roll excitation moment (N.m)
P	Propeller pitch
$R(u)$	Ship resistance (N)
$S(\omega,\chi)$	Wave spectrum
$T(n;u)$	Propeller trust (N)
V_A	Advance velocity (m s^{-1})
W	Ship weight (N)
X_W	Wave force in surge (N)
Z	Number of propeller blade
$d(x)$	Draught of ship section (m)
k	Wave number
n	Propeller revolution (rps)
t_p	Trust deduction factor
u	Surge velocity (m s^{-1})
ς_W	Wave amplitude (m)
ξ_G	Position of gravity in global axis (m)
ϕ	Roll angle (rad)
χ	Heading angle from wave direction (deg)
λ	Wave length (m)
ρ	Density of water (kg m^{-3})
ψ	Wave phase angle (rad)

1. INTRODUCTION

Since the International Maritime Oeganization (IMO) decided to revice its intact stability criteria, some researches regarding the intact stability problem in seaways have been conducted by many researchers. The main focus of the researches is ship stability in waves such as in following seas, quartering seas, beam seas and head seas. Several informations about capsizing prhenomena of ship due to ship stability in waves such as pure loss of stability in following and quartering seas, parametric rolling in following and head seas as well as roll resonance problem in bea mesas and surfriding following boaching in following and quartering seas have been obtained in last decade. In cases of pure loss of stability and parametric rolling, the dangerous condition arise due to large roll angle excited by alteration of restoring arm in waves. Based on these research results, the IMO decided to formulate the new generation of intact stability criteria in order to avoid possibility of dangerous condition due to those three phenomena. In other hand, the present intact stability criteria especially restoring arm characteristics namely area under the restoring arm curve up to certain heel angle, initial metacentric height, weather criteria as well as maximum heel angle due to heeling moments such as wind, passenger and turning moments.

The main structure of the new generation of intact stability criteria shown in Figure 1 has been agreed in the meeting of Intact Stability Correspondence Group (ISCG) developed by the IMO in 2011. As mentioned before that the general criteria and weather criteria in the present stability criteria still included in the new one. If the evaluated ship comply with both general and weather criteria then evaluation continued to dead ship condition, pure loss of stability, parametric rolling and surf-riding or broaching. Except the dead ship condition, the new criteria consists of vulnerability criteria level one, level two, direct assessment using numerical simulation and operation guidance. In case of dead ship condition, the group agreed to use capsizing probability approach under consideration that roll motion equation can be modelled as single degree of freedom and may be solved by linearization of the damping coefficient and restoring arm as propsed by Belenky [1], Bulian and Francescutto [2] and Paroka et. al. [3].

The new criteria for the last three dangerous conditions still under discussion because these phenomena depend to several variables and effect of its nonlinearity effect is significant. Therefore the evaluation methodology was separate into vulnerability level one, vulnerability level two, direct assessment and operation guidance. Some researches regarding the evaluation methodology for each level evaluation have been conducted by some researches.



Gambar 1. Pendekatan evaluasi dari criteria stabilitas yang baru

In case of vulnerability criteria level one for pure loss of stability, Kubo, et. al. [4] proposed that dangerous condition for ship operating in following seas when the metacentric height estimated using the transverse moment of inertia of flat waterplan at the worst water level is negative. For the vulnerability criteria level two they propose the maximum restoring arm hydrostatically calculated with the worst sinusoidal wave surface. Belenky et. al. [5] proposed that the vulnerability criteria level one for pure loss of stability in following wave is described by the average of the vertical wall-sideness coefficient for the fore and after section of the ship. The dangerous condition may occur when the average vertical wall-sideness coefficient of the after body and the fore body of the ship is less than 0.75. The two proposals are actually similar because the nominal prismatic coefficient depends on waterline coefficient and regarding the minimum and maximum draught describe by the block coefficient of the ship. Regarding the vulnerability criteria level two for pure loss of stability in following waves, Bulian [6] proposed a probability approach under assumption that the roll damping coefficient is negligible small and applied the method to estimate probability of pure loss of stability of a container ship in irregular waves.

For ships with small draught or large ratio between breadth and draught, the possibility of negative metacentric height, significantly fluctuation of waterplan area and average of the vertical wall-sideness coefficient less than 0.75 when operating if following and quartering seas is very small. However, small alternation of restoring arm in waves may excite large roll angle due to initial heeling and very small damping coefficient of roll. Therefore a direct assessment for pure loss of stability in following and quartering seas for such ships is necessary in oreder to identify possibility of dangerous condition and effect of some variables on roll motion.

An example of ships with small draught and large ratio between breadth and draught is ro-ro ferry used as inter islands transportation in Indonesia. These ships have also quite small freeboard in order to easily operate the ship regarding the port condition. As a result, most of Indonesian ro-ro ferry could not comply with the IMO general criteria especially heel angle with maximum restoring arm less than 25 degrees [7] and [8]. However those ships still safely operate even several capsizing occur within the last decade. Generally the Indonesian ro-ro ferry may safely operate in Indonesian seaways in dead ship condition (beam seas) with capsizing probability less than the minimum accepted capsizing probability for public facility [8]. In order to ensure the safety of Indonesian ro-ro ferry in seaways, advance research regarding dangerous condition in seaways especially in following and quartering seas as well as head seas should be conducted. This is also aim to follow the new generation of intact stability criteria as proposed by the ISCG in Figure 1.

This paper discusses stability of Indonesian ro-ro ferry with large rasio of breadth and draught in following and quartering seas. This is important regarding developing of the new generation of intact stability criteria and validates the proposal vulnerability criteria level one for pure loss of stability submitted by the delegations of some countries in the ISCG. Effect of some variables on pure loss of stability in following and quartering seas such as wave height and direction relative to the ship and ship velocity are also investigate in this paper. The ship is assumed to have an initial heeling angle due to cargo shift in car deck. Several capsizing accident of Indoneian ro-ro ferry occurs due to cargo shift in the car deck because unproperly lashing of the car.

2. ROLL MOTION OF SHIP IN FOLLOWING WAVES

When a ship operates in following seas, wave excitation moment of roll is negligible small. However the ship may be in dangerous condition due to large roll angle especially if the the ship has small average of vertical wall-sideness coefficient or the ship has very small damping coefficient. The roll motion in following and quartering waves excited by the restoring variation depending on ship posisition relative to the wave. The minimum restoring arm occurs in hoggin condition in which the wave crest in the midship and the maximum restoring arm occurs when the wave crest in both the afterpeak and forepeak of the ship. If variation of restoring arm increases, the excited energy will increase. As a result, the roll angle due to restoring variation will also increase. If the ship body extrimly change in vertical direction then the restoring variation may be significant even the wave height is small. This is because the waterline area of the ship in hogging dan sugging condition will significantly change. Therefore some researchers proposed the waterplan area and the average vertical wall-sideness coefficient as the vulnerability criteria level one for the pure loss of stability in following and quartering waves [4] and [5].

Roll motion equation for ships operating in following and quartering seas may be modelled as two degree for freedom model coupled with the surge motion equation following [9]. These equation are developed using the ordinat system shown in Figure 2.

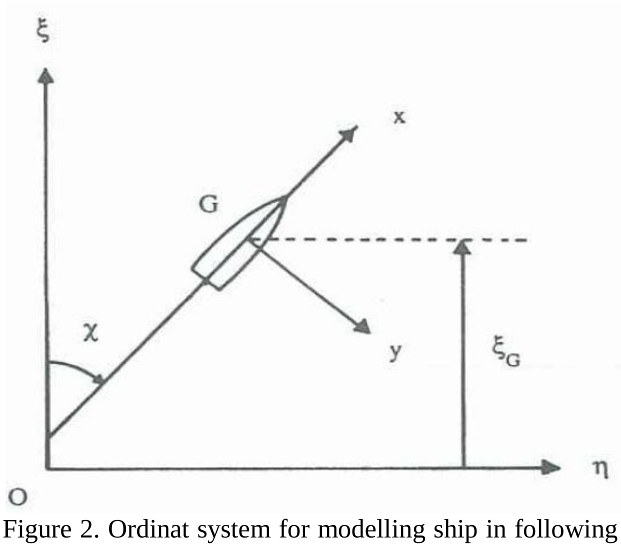


Figure 2. Ordinat system for modelling ship in following and quartering seas.

Here the surge motion equation is necessary in order to obtain the ship posisition in a certain time so that the ship posisition relative to the wave can be obtained for calculating the restoring arm. The two degree of freedom model can be written as follows.

$$(W + A_{11})\dot{u} - R(u) + T(n,u) = X_w(\xi_G/\lambda, \chi) \quad (1)$$

$$(I_{xx} + A_{44})\ddot{\phi} + B_L\dot{\phi} + B_N\dot{\phi} + W\big(GZ_s(\phi) + GZ_w(\phi,t)\big) = M_w(\chi,t) \quad (2)$$

The ship resistance as a function of surge velocity in the equation (1) are estimated by using the Holtrop Method for several surge velocities in calm water in order to obtain polynomial fungsi of the ship resistance as function of forward velocity.

The propeller trust as a function of propeller revolution and surge velocity is estimated using the following equation:

$$T(n,u) = \left(1 - t_p\right)\rho n^2 D^4 K_T(J) \quad (3)$$

where the thrust coefficient of propeller is estimated using the polynomial equation as shown in equation (4).

$$\mathrm{K}_T(J) = \sum_{n=1}^{39} C_n(J)^{S_n}\left(P/_D\right)^{t_n}\left(A_E/_{A_0}\right)^{u_n}(Z)^{v_n} \quad (4)$$

Value of each coefficient in the equation (4) is estimated based on statistical data of B Series propeller as a function of advance velocity [10]. Therefore, the coefficient thrust of propeller can be estimated for variation of ship velocity so that it can be modelled as polynomial equation in order to obtain propeller thrust in a certain ship velocity using the equation (3).

Surge wave force in the equation (1) may be estimated using the method developed by Umeda and Renilson [11] as follows:

$$X_w(\xi_G/\lambda, \chi) = \rho g \varsigma_w k\, cos\chi \int_{AE}^{FE} C_1(x)\, S(x) e^{-\frac{kd(x)}{2}} \times \sin k(\xi_G + x\, cos\chi)\, dx \quad (5)$$

Coefficient C_1 in this equation for each ship section may be estimated using the following equation [12]:

$$C_1(x) = \frac{\sin(k\ \sin\chi\, .\, B(x)/2)}{k\ \sin\chi\, .\, B(x)/2} \quad (6)$$

If the surge velocity has been estimated using the equation (1), the ship posisition relative to the wave can be estimated. Based on this ship position, the restoring arm in calm water and wave may be estimated, respectively. Finally the roll angle can be obtained by solving the equation (2).

3. SHIP DATA AND CALCULATION METHOD

The ship data use in this paper is a ro-ro ferry 600 GT operating as intern island transportation in Indonesia.

This ship is desgned and duilt by national shipyard. The main dimension and ratio of main dimension as well as her body plan respectively are shown in Table 1 and Figure 3 as follow.

Table 1. Principle dimension of a ro-ro ferry 600 GT

Items		Values
Length between perpendicular (Lbp)	m	40.00
Breadth (B)	m	12.00
Draught (T)	m	2.15
Height (H)	m	3.20
Linear damping coefficient (B_L)	s^{-1}	0.008
Nonlinear damping coefficient (B_N)	rad^{-1}	0.0005
B/T	-	5.58
H/T	-	1.49
L/B	-	3.33
L/H	-	12.5

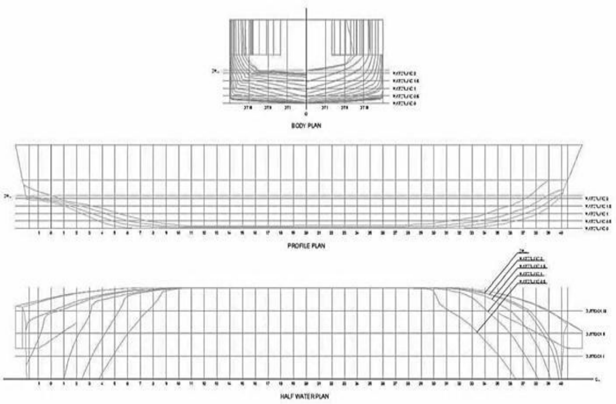


Figure 3. Body plan of subject ship

Characteristics hydrodynamics such as added inertia is estimated by using the strip theory. The roll damping coefficient both linear and nonlinear is estimated by using Ikeda semi empirical method. The surge wave force and the restoring arm in waves are estimated using irregular waves with wave length the same as the ship length. In order to model irregular waves, the ITTC wave spectrum is used and the effective wave profile is modelled by using the Grim effective wave [13]. The wave elevation based on the Grim effective wave can be written as the following equation:

$$\hat{\zeta}_{eff}(x,t) = a(t) + \zeta_{eff}(t)\cos\frac{2\pi}{L}x \qquad (7)$$

dimana:

$$a(t) = \sqrt{2S\,(\omega,\chi)d\omega d\chi}\;F_A\cos(\omega t - kx\cos\chi + \psi)$$

$$\zeta_{eff} = \sqrt{2S\,(\omega,\chi)d\omega d\chi}\;F_C\cos(\omega t - kx\cos\chi + \psi)$$

$$F_A = \frac{\sin Q}{Q}$$

$$F_C = \frac{2Q\sin Q}{(\pi^2 - Q^2)}$$

$$Q = \frac{\omega^2\lambda}{2g\cos\chi}$$

In order to obtain effect of some variable on pure loss of stability in following and quartering waves such the wave height, the wave direction and ship velocity, numerical simulation in time domain is conducted with several different values of those variables. The ship velocity is determined by variated the propeller revolution with assumption that the power and the propeller characteristic are constant. This means that alteration of ship velocity only due to variation of the propeller revolution.
The range of ship velocity used for estimating the resistance is 6 – 15 knots. Based on the estimation results, polynomial equation of ship resistance as a function of ship velocity may be developed. Realtionship between the ship velocity and ship resistance is shown in Figure 4 and its polynomial equation shown in the equation (8).

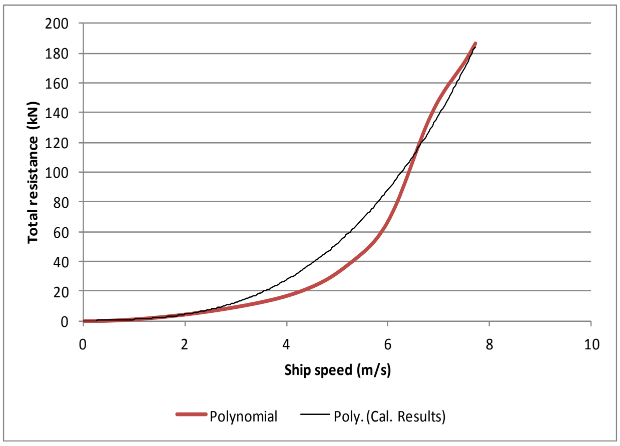


Figure 4. Ship resistance as function of ship velocity

$$R(u) = 0.3904u^3 + 0.6525u \qquad (8)$$

Using the equation (4) for the same variation of ship velocity as the estimation of ship resistance, the thrust coefficient as function of advance velocity can be estimated. Here, the number of propeller blade, propeller diameter and aspect ratio of propeller are assumed to be constant. Variation of ship velocity occurs due to alteration of the propeller revolution. The obtained thrust coefficient for each advance velocity is shown in Figure 5. The polynomial equation of the thrust coefficient as function of advance velocity is shown in the equation (9).

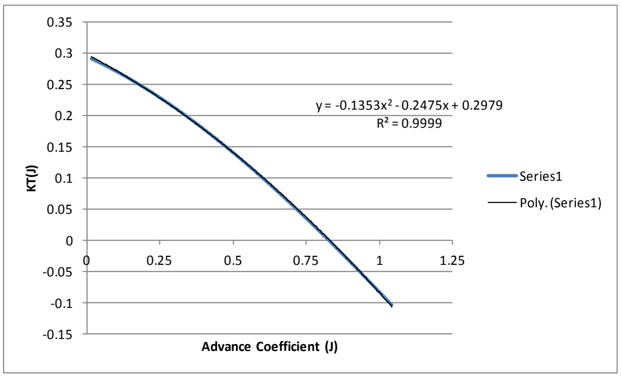


Figure 5. Thrust coefficient of propeller as function of advance velocity

$$K_T(J) = -0.1353J^2 - 0.2475J + 0.2979 \qquad (9)$$

where

$$J = \frac{V_A}{nD}$$

In order to obtain roll motion response, the equation (1) and (2) are solved in time domain using the second order Runga-Kutta method. The restoring arm in wave is calculated by considering the static trim with pressure due to both calm water and Froud-Krylov force. The subject ship is assumed to have an initial heel angle due to cargo shift on car deck. This condition is possible to occur in Indoensian ro-ro ferry escpecislly when the ship operates in rough weather.

In order to investigate effect of wave, the calculation in conduted for wave height form 1.50 meters up to 2.25 meters. The heading angle from wave direction is simulated from 0 degress up to 45 degrees with increasing of 15 degrees. The wave exciting moment for the heading angle geater than 0 degrees is neglected so that the roll motion only excited by the restoring arm variation in wave.

Effect of ship velocity on roll motion in following and quartering seas is investigated by changing the propeller revolution in order to obtain different ship velocity. Here three different propeller revolution are used which are propeller revolution for service speed, less than the propeller revolution for service speed and the last one is higher than the propeller revolution for service speed.

4. RESULTS AND DISCUSSION

4.1 EFFECT OF SIGNIFICANT WAVE HEIGHT

The roll motion for each significant wave height with heading angle nol degrees and the ship velocity the same as the service speed is shown in Figure 6. Here the simulation is conducted for time duration of 1500 seconds.

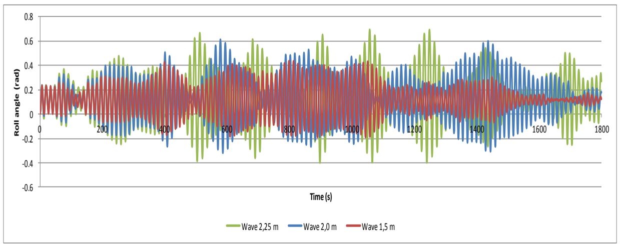


Figure 6. Roll motion for three different significant wave heights. The heading angle is 0 degress.

Figure 6 shows that the maximum amplitude of roll motion increases when the significant wave height increases. This is because the variation of restoring arm in wave increases when the significant wave height increases. Even the average of vertical wall-sideness coefficient is larger than 0.75 and the metacentric height in hogging condition for all significant wave heights is posisitve, the restoring arm variation may be significant due to significantly changes of ship body above the maximum draught especially both afterpeak and forepeak. Variation of restoring arm for significant wave height of 2.0 meters is shown in Figure 7. The alteration of the restoring arm variation for each significant wave height is smaller compared with the restoring variation of the container ship using by IMO as sample ship in the developing of the new generation intact stability criteria [9]. The large roll angle here may be also caused by small damping coefficieny of roll motion.

Within the duration of simulation, occurrence of capsizing is not identified in all significant wave heights and the roll motion is still stable. However the large roll angle mainly when the significant wave height is 2.25 meters, deck edge of the ship may immerced in seawater. This condition could be followed by another dangerous condition such as decreasing the ship stability due to trapped water on deck. As mentioned before that the Indonesian ro-ro ferries mostly have small freeboard, large roll angle should be considered as a dangerous condition even the roll motion still stable.

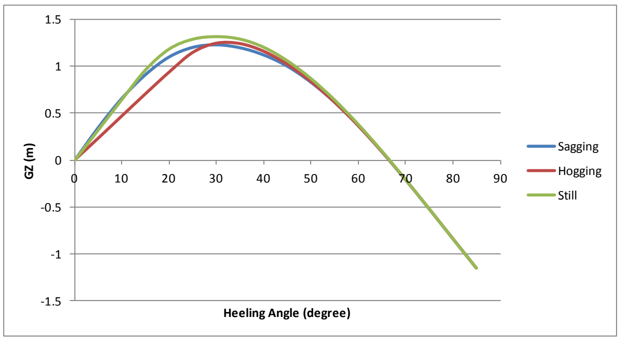


Figure 7. The restoring arm in calm water and wave. The significant wave height is 2.0 meters.

In the higher significant wave height for example 2.50 meters, dangerous capsizing occurs in which the roll motion become unstable or the pure loss of stability occurs after several second simulation. The time history of the capsizing is shown in Figure 8. Here the heading angle from wave direction is 0 degrees and the initial forward speed is 5.13 m/s. The roll angle increases with the exposure time and finally capzises.

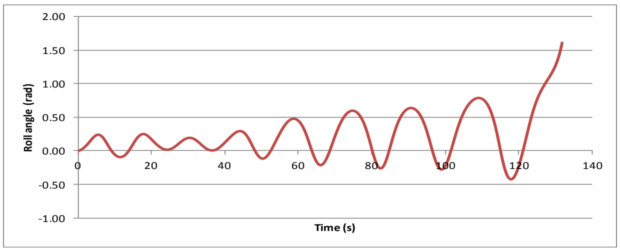


Figure 8. Roll motion of the subject ship for significant wave height of 3.00 meters. The heading angle is 0 degrees and initial forward speed is 5.13 m/s.

Regarding the vulnerability criteria level one for pure loss of stability in following and quartering wave proposed by delegations of some countries such as United States and Japan should be validated with different ships typology with the used topology when the criteria is developed. One variable should be considered in the new criteria is amplitude of restoring arm variation in wave as the factor induces roll motion in following and quartering seas. The dangerous condition may be identified when the difference of restoring arm in hogging and sugging condition excees a certain value which should be investigated in advance using several ship topology. This parameter may be combined with the roll damping coefficient as the one factor to avoid dangerous condition in following and quartering seas.

4.2 EFFECT OF HEADING ANGLE

Roll motion in following and quartering seas with heading angle from wave direction 0 degrees to 45 degreees with increasing of 15 degrees is shown in Figure 8. Here, the significant wave height is 2.25 meters and the time duration of simulation is 1500 seconds. The ship speed the same as the service speed of the subject ship. The sway motion and the wave exciting moment of roll are neglected. This means that the roll motion occurs purely due to the restoring arm variation in wave.

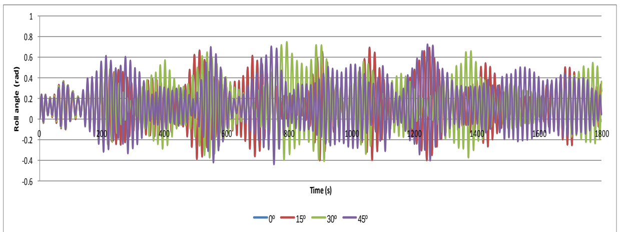


Figure 9. Roll motion for several heading angle from wave direction. The significant wave height is 2.25 meter.

The Figure 9 shows that maximum amplitude of roll motion is not significantly change due to variation of heading angle. This results show that alteration of heading angle from wave direction does not affect the restoring arm variation. Effect of the heading angle from wave direction may be identified when the effective wave length is larger than the ship length. It means that th effective length of wave for the heading angle will be the same as the ship length. The heading angle from wave direction affects only encounter frequency. Therefore the maximum amplitude of roll motion does not change but the maximum amplitude of roll occurs in different time for different heading angle from wave direction. In the initial time of simulation, the roll angle for all heading angle is relatively the same but different patern of roll motion arises in the next duration time of simulation.

Based on the above explanations, it can be concluded that the heading angle from wave direction has no effect on the amplitude of roll motion. In the real situation, the roll angle with larger heading angle is larger than that with smaller heading angle. This is because effect of wave exciting moment wich will increase by increasing the deading angle up to the heading angle of 90 degrees (beam seas condition). The resonance roll motion may be the other dangerous condition for the ship in this heading angle. In case of long wave, the surf-riding phenomena may occur followed by broaching. In order to investigate such dangerous condition, Umeda, et. al. [14] recommends a six degree of freedom mathematic model. Changing the ship direction relative to the wave is not recommended solution to avoid the pure loss of stability in following and quartering seas.

4.3 EFFECT OF SHIP SPEED

When a ship operates in following and quartering seas, the ship speed will affect the encounter frequency and the time spent by the ship in a position relative to the wave. The spent time in a relative position to the wave will directly influence the periode of restoring arm variation as the particular variables induce the roll motion.

Results of roll motion simulation for several initial forward speeds of the subject ship in significant wave height of 2.25 meters with the heading angle from wave direction of 0 degrees are shown in Figure 10.

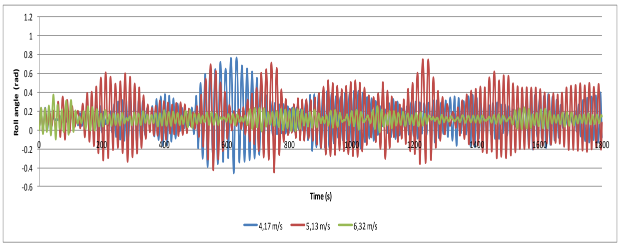


Figure 10. Rol motion of the subject ship for three intial forward speeds. The significant wave height is 2.25 meters and the heading angle is 0 degrees.

The amplitude of roll angle tends to decrease when the initial forward speed increases. However in an intial forward speed the amplitude increases as the initial forward speed increases. This peak amplitude occurs in several initial forward speeds but the value of amplitude decreases for higher initial forward speed. The alteration of roll motion amplitude due to variation of the initial forward speed is shown in Figure 11.

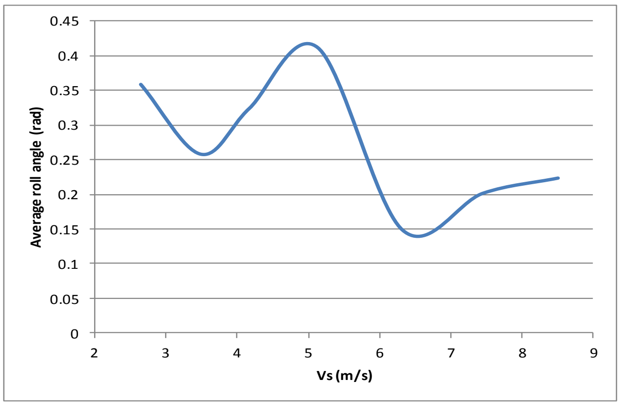


Figure 10. Th amplitude of roll motion for several initial forward speeds. The significant wave height is 2.25 meters and the heading angle is 0 degrees.

In a low intial forward speed, the wave encounter frequency is high. As a result, the period of restoring arm variation in wave also increases.Therefore the amplitude of roll motion tends to increase. By increasing the intial forward speed, the wave encounter frequency decreases and the period of restoring arm variation decreases. The ship will run with the wave for a longer duration of time. In the duration of time, the restoring arm tends to be constant. The amplitude of roll angle decreases because of contant restoring arm when the initial forward speed increases.

For a certain initial forward speed, the amplitude of roll angle increases due to increase of the initial forward speed. This is because of wave encounter frequency in such initial forward speed is the same as the natural frequency of roll. This means that the larger amplitude of roll angle due to resonance of roll motion. The resonance occurs when the wave encounter frequency is the same as multiple of the natural roll frequency. Eventhough, the resonance amplitude dercreases when the resonance frequency decreases or the initial forward speed increases. This phenomena is also caused by periode of restoring arm variation tends to be small in lower of resonance frequency. This fact shows that large roll angle or pure loss of stability in following and quartering seas can be avoided by change the ship speed. However, the other dangerous condition should be considered such as broaching phenomena in long wave cases.

5. KESIMPULAN

Based on the above calculation results and discussion, some conclusions can be remark as follows:

1. Capsizing dangerous due to pure loss of stability in following and quartering seas is not identified when the significant wave height smaller than 2.25 meters. However capsizing may occur if the significant wave height is larger than 2.25 meters. It means that the significant wave height significantly affects roll motion in following and quartering seas.
2. The maximum roll angle of the ship does not significantly change due to alteration of the heading angle from wave direction. It means that the heading angle form wave direction has no significant effect on roll motion in following and quartering seas. This fact shows that dangerous condition in following and quartering seas cannot be avoided by changing the heading angle from wave direction.
3. The initial forward speed has significant effect on roll motion in following and quartering seas because the periode of reastoring arm variation as the main factor affect the roll motion depends on the ship speed relative to the wave. The other reason is the ship may experience resonance roll motion when the ship speed induce encounter frequency the same as the natural frequency of roll. These facts shown that the large roll angle or dangerous of pure loss of stability in following and quartering seas can be avoid by changing the ship speed. Therefore vulnerability criteria of direct assessment and guidance operation are necessary in the new generation of intact stability criteria.

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